A Note on Crossing the Phantom Divide in Hybrid Dark Energy Model

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Abstract

Recently a lot of attention has been given to building dark energy models in which the equation-of-state parameter w can cross the phantom divide $w = -1$. However, to our knowledge, these models with crossing the phantom divide only provide the possibility that w can cross -1. They do not answer another question: *why crossing phantom divide occurs recently?* Since in many existing models whose equation-of-state parameter can cross the phantom divide, w undulates around -1 randomly, *why are we living in an epoch $w < -1$?* This can be regarded as the second cosmological coincidence problem. In this note, we propose a possible approach to alleviate this problem within a hybrid dark energy model.

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Many cosmological observations, such as SNe Ia [1], WMAP [2], SDSS [3], Chandra X-ray Observatory [4] etc., discover that our universe is undergoing an accelerated expansion. They also suggest that our universe is spatially flat, and consists of about 70% dark energy with negative pressure, 30% dust matter (cold dark matters plus baryons), and negligible radiation. Dark energy has been one of the most active fields in modern cosmology [5].

In the observational cosmology of dark energy, the equation-of-state parameter (EoS) $w \equiv p/\rho$ plays a central role, where p and ρ are its pressure and energy density, respectively. To accelerate the expansion, the EoS of dark energy must satisfy $w < -1/3$. The simplest candidate of the dark energy is a tiny positive time-independent cosmological constant Λ, for which $w = -1$. However, it is difficult to understand why the cosmological constant is about 120 orders of magnitude smaller than its natural expectation, i.e. the Planck energy density. This is the so-called cosmological constant problem. Another puzzle of the dark energy is the cosmological coincidence problem: *why are we living in an epoch in which the dark energy density and the dust matter energy density are comparable?* This problem becomes very serious especially for the cosmological constant as the dark energy candidate. The cosmological constant remains unchanged while the energy densities of dust matter and radiation decrease rapidly with the expansion of our universe. Thus, it is necessary to make some fine-tunings. In order to give a reasonable interpretation to the cosmological coincidence problem, many dynamical dark energy models have been proposed as alternatives to the cosmological constant. The famous one is quintessence [6, 7, 36], a cosmic real scalar field that is displaced from the minimum of its potential. With the evolution of the universe, the scalar field slowly rolls down its potential. The Lagrangian density for the quintessence is

$$\mathcal{L}_{quintessence} = \frac{1}{2} \left(\partial_\mu \varphi \right)^2 - V(\varphi), \tag{1}$$

where φ is a real scalar field, and we adopt the metric convention as $(+, -, -, -)$ and use the units $\hbar = c = 8\pi G = 1$ throughout this note. A class of tracker solutions of quintessence is found in order to solve the cosmological coincidence problem [7]. Another famous dark energy candidate is phantom [8, 9, 10, 37], which has a "wrong" sign kinetic energy term, i.e.

$$\mathcal{L}_{phantom} = -\frac{1}{2} \left(\partial_\mu \varphi \right)^2 - V(\varphi). \tag{2}$$

It is easy to see that the EoS of quintessence (phantom) is always larger than (less than) -1.

Recently, by fitting the SNe Ia data, marginal evidence for the EoS of dark energy $w(z) < -1$ at redshift $z < 0.2$ has been found [11]. In addition, many best-fits of the present value of w are smaller than -1 in various data fittings with different parameterizations (see [12] for a recent review). The present data seem to slightly favor an evolving dark energy with w crossing -1 from above to below in the near past [13]. Obviously, the EoS w cannot cross the so-called phantom divide $w = -1$ for quintessence or phantom alone. Some efforts [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 34, 35] have been made to build dark energy model whose EoS can cross the phantom divide. However, to our knowledge, many of the existing models only provide the possibility that w can cross -1. They do not answer another question: *why crossing phantom divide occurs recently?* Since in many existing models whose EoS can cross the phantom divide, w undulates around -1 randomly, *why are we living in an epoch $w < -1$?* It can be regarded as the second cosmological coincidence problem.

In this note, we propose a possible approach to alleviate the so-called second cosmological coincidence problem. The key point is the *trigger* mechanism. It is reminiscent of the well-known hybrid inflation [30], which arises naturally in many string/brane inspired inflation models (see e.g. [31] for a

comprehensive review). In the hybrid inflation model, the effective potential is given by

$$V(\phi,\sigma) = \frac{1}{2}m^2\phi^2 + \frac{g^2}{2}\phi^2\sigma^2 + \frac{1}{4\lambda}\left(M^2 - \lambda\sigma^2\right)^2,$$
(3)

where ϕ and σ are two canonical real scalar fields, and play the roles of inflaton and the "waterfall" field, respectively. The feature of spontaneous symmetry breaking in the hybrid inflation model is critical. At the first stage, the field σ is trapped to $\sigma = 0$, while the field ϕ slowly rolls down and drives the inflation. When the field ϕ reaches a critical value ϕ_c, the field σ is triggered and starts to roll down rapidly. And then, the inflation ends. Recently, Gong and Kim in [32] have proposed a model, which can describe simultaneously the primordial inflation and present accelerated expansion of the universe (see [38] also), by employing a mechanism similar to the hybrid inflation. In their model, three canonical real scalar fields ϕ, ψ and σ appear, and play the roles of inflaton, transition field and quintessence, respectively. The effective potential is given by

$$V(\phi,\psi,\sigma) = \frac{1}{2}m^2\phi^2 + \frac{g^2}{2}\phi^2\psi^2 - \frac{h^2}{2}\psi^2\sigma^2 + \frac{1}{4\lambda}\left(M_\psi^2 - \lambda\psi^2\right)^2 + \frac{1}{4\mu}\left(M_\sigma^2 + \mu\sigma^2\right)^2.$$
(4)

It is worth noting that the third and fifth terms involved σ are different from the other terms involved ϕ and ψ, which are similar to those in the hybrid inflation model. As was argued in [32], this kind of effective potential may arise from the supersymmetric theories. In this model, there are three different stages. At the first stage, the fields σ and ψ are trapped to $\sigma = 0$ and $\psi = 0$, while the field ϕ slowly rolls down and drives the primordial inflation. When ϕ reaches a critical value ϕ_c, the transition field ψ is triggered to roll down and the primordial inflation ends. When ψ rolls down to a critical value ψ_c, the quintessence field σ is triggered to slowly roll down its potential and drives the present accelerated expansion.

Enlightened by the hybrid inflation model [30] and the model by Gong and Kim [32], we find that the trigger mechanism can be employed to alleviate the so-called second cosmological coincidence problem mentioned above. Since our interest is the issue of dark energy problem, here we consider a model with two real scalar fields, rather than three real scalar fields like [32]. Note that the fields appear in either the hybrid inflation model [30] or the work of Gong and Kim [32] are all quintessence-like canonical real scalar fields, namely their kinetic energy terms are all positive. Thus, their EoS are always larger than -1. However, our main aim here is to implement a mechanism for crossing the phantom divide. To this end, we employ a quintessence and a phantom in our model. The effective potential in our model is

$$V(\phi,\sigma) = \frac{1}{2}m^2\phi^2 - \frac{g^2}{2}\phi^2\sigma^2 + \frac{1}{4\lambda}\left(M^2 + \lambda\sigma^2\right)^2,$$
(5)

where m, M, g and λ are all positive constants; the field ϕ is a quintessence with kinetic energy term $\dot{\phi}^2/2$, the field σ is a phantom with kinetic energy term $-\dot{\sigma}^2/2$, and we have supposed that they are spatially homogeneous; a dot denotes the derivative with respect to cosmic time t. Actually, in some sense our hybrid dark energy model is similar to the quintom model [21, 22, 23, 13] or the hessence model [19]. The key difference is the interaction form between quintessence and phantom, and especially the effective potential with the feature of spontaneous symmetry breaking. We will see that this key difference makes this simple model have rich phenomenology and provide the possibility to alleviate the so-called second cosmological coincidence problem.

Note that the quintessence *rolls down* its potential and approaches to stabilize at the *minimum* [6], while the phantom *climbs up* its potential and approaches to stabilize at the *maximum* [10]. We show

the 3D plot of the effective potential (5) in Fig. 1. To determine the extrema of the effective potential (5), it is useful to work out the first and second derivatives in the σ and ϕ directions, respectively. They are

$$V_{,\sigma} = \left(M^2 - g^2\phi^2 + \lambda\sigma^2\right)\sigma\,, \qquad (6)$$

$$V_{,\sigma\sigma} = M^2 - g^2\phi^2 + 3\lambda\sigma^2\,, \qquad (7)$$

and

$$V_{,\phi} = \left(m^2 - g^2\sigma^2\right)\phi\,, \qquad (8)$$

$$V_{,\phi\phi} = m^2 - g^2\sigma^2\,, \qquad (9)$$

where $f_{,x} \equiv \partial f/\partial x$. Following the hybrid inflation model [30] and the work of Gong and Kim [32], for convenience, we only consider the case of $\phi \geq 0$ and $\sigma \geq 0$, since the effective potential (5) is symmetric. Therefore we have,

$$V_{,\phi\sigma} = V_{,\sigma\phi} = -2g^2\phi\sigma \leq 0. \qquad (10)$$
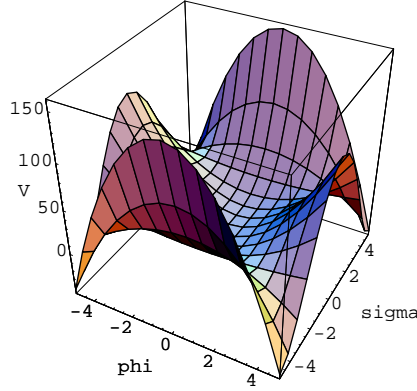

Figure 1: The 3D plot of the effective potential (5) for demonstrative model parameters $g = \lambda = 1$, $m = 3$ and $M = 0.1$.

For $\phi > \phi_c \equiv M/g$, from Eq. (6), we have three extrema for the effective potential (5) in the σ direction, i.e.

$$\sigma = 0 \qquad \text{and} \qquad \sigma = \sigma_\pm \equiv \pm\sqrt{\frac{g^2\phi^2 - M^2}{\lambda}}. \qquad (11)$$

From Eq. (7), we see that $\sigma = 0$ is the only maximum while $\sigma = \sigma_\pm$ are minima. See Fig. 2. Recall that the phantom *climbs up* its potential and approaches to stabilize at the *maximum* [10]. To trap the field σ at the maximum $\sigma = 0$ in the first stage, we assume that the initial value of the field σ satisfies $\sigma_-|_{\phi=\phi_{ini}} < \sigma_{ini} < \sigma_+|_{\phi=\phi_{ini}}$. If the initial value of ϕ, namely ϕ_{ini}, is large enough, or by appropriately choosing the parameters g, λ and M, we can make $|\sigma_\pm|$ large enough. Therefore, the range (σ_-, σ_+) is
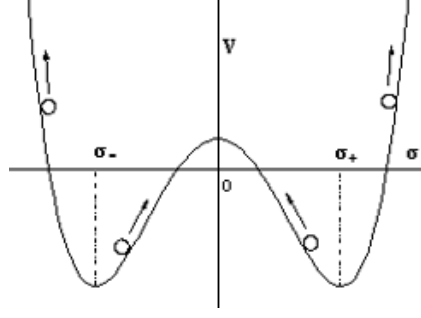
Figure 2: The sketch of the effective potential (5) in the σ direction for $\phi > \phi_c$.

wide enough and needs not fine-tuning. Hence, in the first stage, we expect that the phantom field σ is trapped to $\sigma = 0$, whereas the quintessence field ϕ could remain large and slowly roll down its potential for a long time. In this case, the kinetic energy term of the field σ vanishes, namely, $-\dot{\sigma}^2/2 = 0$. The hybrid dark energy reduces to the case of a quintessence with an effective cosmological constant. In this stage, the effective EoS remains larger than -1 for a long time.
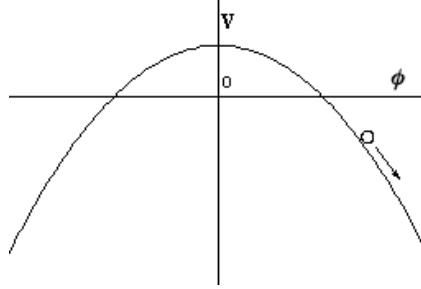

Figure 3: The sketch of the effective potential (5) in the ϕ direction for $\sigma > \sigma_c$.

When ϕ becomes smaller than ϕ_c, a phase transition for σ takes place. However, the thing is not so simple. From Eqs. (8) and (9), $\phi = 0$ is the minimum only when $\sigma < \sigma_c \equiv m/g$. If $\sigma > \sigma_c$, $\phi = 0$ is maximum and the field ϕ becomes larger and larger. See Fig. 3. Thus, ϕ cannot reach ϕ_c forever and the phase transition cannot happen. To realize the phase transition, we assume that $\sigma_c > \sigma_+|_{\phi=\phi_{ini}}$. So, in the first stage, $\sigma < \sigma_c$ always holds and the field ϕ rolls down toward its minimum $\phi = 0$. When $\phi < \phi_c$, from Eqs. (6) and (7), $\sigma = 0$ becomes the only minimum where the phantom field σ is unstable. As a result, when ϕ reaches the critical value ϕ_c, the phase transition occurs and the phantom field σ is triggered to climb up its potential. The kinetic energy term of the phantom field σ, namely $-\dot{\sigma}^2/2$, becomes more and more negative as the velocity of σ increases. On the other hand, the quintessence field ϕ rolls down its potential and approaches to its minimum $\phi = 0$ and stabilize there after some periods of oscillation. Once ϕ is trapped at $\phi = 0$, its kinetic energy term $\dot{\phi}^2/2 = 0$. Thus, the hybrid dark energy model reduces to the one for a pure phantom field. Therefore the effective EoS remains smaller than -1. Crossing the phantom divide occurs between the moment of phase transition $\phi = \phi_c$ and the moment of ϕ being trapped at $\phi = 0$ eventually.

This is not the whole story. When σ continuously climbs up, it will eventually arrive at the critical value σ_c mentioned above. When $\sigma > \sigma_c$, from Eqs. (8) and (9), $\phi = 0$ becomes a maximum. The quintessence field ϕ is triggered to roll down again. This is a new feature, which does not appear in the hybrid inflation model [30] and the model given by Gong and Kim [32]. In the third stage, the quintessence field ϕ rolls down and its value increases continuously. When ϕ reaches the critical value ϕ_c once again, the motion of σ will not change the direction and σ continues to climb up, since at this moment $\sigma > \sigma_c > \sigma_+|_{\phi=\phi_{ini}} \gg \sigma_+|_{\phi=\phi_c}$ because of $\phi_{ini} \gg \phi_c$ [cf. Eq. (11) and Fig. 2]. In this stage, the effective EoS is involved. Note that crossing the phantom divide occurs when $\dot{\phi}^2 = \dot{\sigma}^2$. In this stage, the veloities of ϕ and σ are all increasing. Therefore, whether the EoS remains smaller than -1 or changes to be larger than -1 depends on the profile of the effective potential (5) in the third stage.
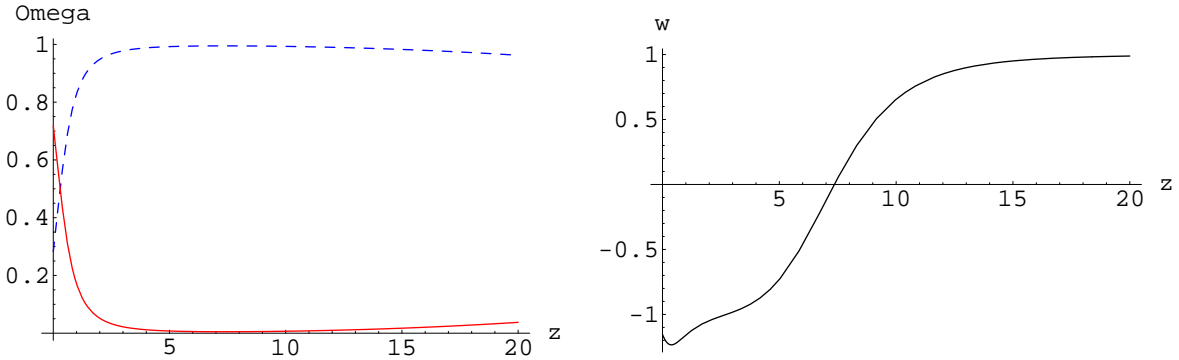

Figure 4: The numerical plots for the demonstrative parameters $\bar{g} = \bar{\lambda} = \bar{m} = \bar{M} = 1$ and $\Omega_{m0} = 0.3$. The left panel is the fractional energy densities of hybrid dark energy (solid line) and dust matter (dashed line) versus redshift z. The right panel is the effective EoS of hybrid dark energy versus z.

In this note we are concerned for the second stage. In this stage, crossing the phantom divide occurs with the help of the trigger mechanism. The effective EoS remains smaller than -1 in the major part of this stage. We can choose the model parameters to make σ_c large enough. So, the duration of the second stage can be long enough. Following the idea proposed in [33], if the fraction of the duration of the second stage to the lifetime of our universe is large enough, the probability that we live in this stage is also large enough. On the other hand, by appropriately choosing model parameters, we can construct a cosmological model so that crossing the phantom divide occurs when the dark matter energy density and dark energy density are comparable. In this sense, the so-called second cosmological coincidence problem can be alleviated.

To support this point, we present a numerical demonstration here. The equations of motion for ϕ and σ are

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0, \qquad \ddot{\sigma} + 3H\dot{\sigma} - V_{,\sigma} = 0, \tag{12}$$

respectively. Considering a spatially flat universe, the Friedmann equation reads

$$H^2 = \frac{1}{3}\left(\rho_m + \rho_X\right), \tag{13}$$

where we have used the unit $8\pi G = 1$. The effective pressure and energy density of the hybrid dark energy are

$$p_X = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}\dot{\sigma}^2 - V(\phi,\sigma), \qquad \rho_X = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}\dot{\sigma}^2 + V(\phi,\sigma), \tag{14}$$

respectively, where the effective potential $V(\phi,\sigma)$ is given by Eq. (5). The effective EoS of the hybrid dark energy $w \equiv p_X/\rho_X$. For convenience, we consider the case of minimal coupling between dark energy and dust matter, thus

$$\rho_m = \rho_{m0}a^{-3}, \tag{15}$$

where the subscript "0" indicates the present value of the corresponding quantity, $a = (1+z)^{-1}$ is the scale factor (we set $a_0 = 1$ throughout), and z is the redshift. Then, we recast Eqs. (12) and (13) as the following first-order differential equations with respect to the redshift z,

$$\frac{d\phi}{dz} = -(1+z)^{-1}\bar{H}^{-1}\bar{\chi}, \tag{16}$$

$$\frac{d\sigma}{dz} = -(1+z)^{-1}\bar{H}^{-1}\bar{\eta}, \tag{17}$$

$$\frac{d\bar{\chi}}{dz} = (1+z)^{-1}\left[3\bar{\chi} + \left(\bar{m}^2 - \bar{g}^2\sigma^2\right)\phi\bar{H}^{-1}\right], \tag{18}$$

$$\frac{d\bar{\eta}}{dz} = (1+z)^{-1}\left[3\bar{\eta} - \left(\bar{M}^2 - \bar{g}^2\phi^2 + \bar{\lambda}\sigma^2\right)\sigma\bar{H}^{-1}\right], \tag{19}$$

and

$$\bar{H}^2 = \Omega_{m0}(1+z)^3 + \frac{1}{3}\left[\frac{1}{2}\bar{\chi}^2 - \frac{1}{2}\bar{\eta}^2 + \frac{1}{2}\bar{m}^2\phi^2 - \frac{1}{2}\bar{g}^2\phi^2\sigma^2 + (4\bar{\lambda})^{-1}\left(\bar{M}^2 + \bar{\lambda}\sigma^2\right)^2\right], \tag{20}$$

where $\bar{\chi} \equiv \dot{\phi}/H_0$, $\bar{\eta} \equiv \dot{\sigma}/H_0$, $\bar{m} \equiv m/H_0$, $\bar{M} \equiv M/H_0$, $\bar{g} \equiv g/H_0$, $\bar{\lambda} \equiv \lambda/H_0^2$, $\bar{H} \equiv H/H_0$ and $\Omega_{m0} \equiv \rho_{m0}/(3H_0^2)$. We show the numerical result in Fig. 4. It is easy to see that the effective EoS of hybrid dark energy crosses the phantom divide $w = -1$ when the redshift z is of order unity, while the fractional energy densities of dust matter and dark energy are comparable.

After all, some remarks are in order. Firstly, within the spirit of the hybrid inflation model [30] and the model by Gong and Kim [32], the effective potential (5) could be generalized. For instance, instead of the term $m^2\phi^2/2$, one can use the term $\mu\phi^4/4$ or other possible potentials for the quintessence field ϕ. Secondly, it is also possible in our model to make an alleviation for the "first" cosmological coincidence problem. Note that in the first stage the phantom field σ is trapped at $\sigma = 0$, the hybrid dark energy model reduces to the one for a pure quintessence. As is well-known, it is easy to obtain a tracker solution for the quintessence [7]. So, it is not strange that we are living in an epoch in which the energy densities of dark energy and matter are comparable. Thirdly, as mentioned above, in the third stage of our model, whether the EoS remains smaller than -1 or comes back to larger than -1 depends on the profile of the effective potential (5). Thus, the avoidance of the big rip is also possible for suitable model parameters. Fourthly, similar to [32], one may add other scalar field into our model to unify the primordial inflation, present accelerated expansion and crossing the phantom divide. Finally, the hybrid-inflation-type models can arise naturally in many string/brane inspired theories (see e.g. [31] for a comprehensive review). And the kind of effective potentials (4) is argued to arise from the supersymmetric theories in [32]. We expect that our hybrid dark energy model in this note has also a solid physical foundation.

Acknowledgments

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